Analysis of McMurdo to South Pole Traverse as a Means to Increase LC-130 Availability in the USAP

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Introduction

The objective of this exercise is to outline and quantify one of the options considered by the NSF Office of Polar Programs in their effort to increase the availability of LC-130 aircraft missions. This NSF goal is directed at shifting to a more favorable balance, the ratio of LC-130 missions spent on infrastructure and general logistics support compared to direct science support. The specific option considered here is that of establishing an oversnow trail and transportation system connecting McMurdo to South Pole. With such a trail, the USAP could shift the bulk of commodities transport from LC-130s to surface vehicles, freeing up the specialized and rare LC-130s for tasks in the "open field" or at minimally prepared skiways, and thereby contributing to the NSF goal.

This study will build on the prior traverse feasibility work (e.g., Evans, 1996), which determined that an oversnow route exists that avoids all but a few crevassed regions and all but one short steep grade (Blaisdell, 1999). Those studies, while encouraging, still leave some critical feasibility issues in question. Additionally, they focused strictly on the technical feasibility of establishing and operating a surface transportation network between McMurdo and South Pole, placing little or no attention on other important aspects of such a scheme. For example, development timelines, cost estimates, risk considerations, and suitable operating procedures (as they integrate into the current USAP field season) were not addressed. The following discussion will document a first attempt to attach these factors to the traverse scheme.

Prior Studies

The concept of an oversnow trail to South Pole has been considered on and off for many years. Recently (starting in 1993) several preliminary and ad hoc studies were conducted by glaciologists and air photo specialists familiar with portions of the Transantarctic Mountains that flank the Ross Ice Shelf. Their goal was to determine, by remote means, which glaciers in the range might be suitable for heavy tractor train travel. Aerial reconnaissance flights as part of other studies within the Transantarctic Mountains were also used to analyze the glaciers.

These initial studies utilized both existing air photos from the USGS map library (some dating back to the 1950's) and recent high-resolution satellite imagery to categorize the many glaciers that could provide access from the Ross Ice Shelf to the polar plateau. The principal concerns were to find routes with even, modest grades and firm, dry snow conditions. More importantly, however, minimal crevassing was desired for the route. A brief history of recent work follows.

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Transantarctic Mountains

The minutes of a 9 June 1993 meeting about South Pole traversing show that a review of Jim Matthews' (Holmes and Narver) independent study of traverse routes was discussed. In Matthew's analysis he identified three glaciers for consideration, the Skelton, the Barnes, and the Scott glaciers. It is not certain why he focused on these three glaciers. His opinion of these routes is as follows.

a. Skelton- First choice by far because of its history of traverses beginning in 1957. Steep grade (7-8% for stretches of 0.25 miles) will require two tractors for a load of 75,000 lbs.

b. Barnes and Scott Glaciers- Distant second and remote third choices, respectively. (This reference to the Barnes Glacier is presumably an error; the Barnes Glacier is on the west side of the Antarctic Peninsula.)

A systematic study of the Transantarctic Range by glaciologists was begun shortly after this meeting. In a 20 July 1993 report "Initial Review of Over-Ice Routes from McMurdo to South Pole," Robert Bindschadler (NASA) assesses the route potential of 20 glaciers from the Skelton to, but not including, the Reedy. Evaluations were based on an analysis of aerial and satellite photographs at the SCAR Library as well as 1:250,000 topographic maps.

This report includes Bindschadler's note stating that the Byrd Glacier was omitted by oversight, but that, "my recollection is that there are sections crevassed across the entire width and it can be discarded as a possible route." Ian Whillans (Byrd Polar Research Center, Ohio State University) subsequently confirmed that the Byrd Glacier is heavily crevassed and out of the question as a tractor route.

Bindschaldler rated the 20 most likely glaciers that the traverse could take; only the Leverett Glacier received an encouraging score of 'Good.' The only adverse comment about the Leverett pertained to the distance from McMurdo. (It wasn't clear why this fact was considered negatively.) Glaciers rated 'Fair' (Table 1) suffered some combination of gradient and crevasse problems that made them seem less than ideal. To warrant a 'Poor' rating substantial gradient and crevasse problems were apparent. A 'Not Practicable' rating signified that crevassing was too severe to allow any reasonable consideration for tractor train movement.

On 26 July 1993, a memorandum by Bob Bindschandler, Jim Matthews, and Ian Whillans based on work they had done together with Bob Allen and D'Ann Lear (both from the USGS) was issued under Ohio State University letterhead (Byrd Polar Research Center). This memo discussed an inspection of aerial photographs of potential tractor train routes through the Transantarctic Mountains. The document refines the categorizations of the above 20 July report as follows.

From the list of glaciers with 'Good' and 'Fair' ratings, three were designated 'Promising'; The Leverett ("long trip on the Ross Ice Shelf required"), the Hatherton ("Trickiest part seems to be at head..."), and the Skelton ("Seems more tricky than other routes"). Two glaciers were noted as 'May be Possible'; the Beardmore and the Shackleton. In spite of this designation strong warnings against both of these glaciers were noted. For example, regarding the Beardmore; "These crevasses probably eliminate this route from possibility for tractors," and for the Shackleton; "There is no hope."

On 22 November 1993 C.R. Bentley (University of Wisconsin) issued a memo to the Senior NSF Representative at McMurdo regarding a reconnaissance of polar plateau access. This memo described a Twin Otter over flight of the Hatherton and Skelton Glaciers made the previous day by him together with Will Harrison (University of Alasks, Geopysical Institute) and Barclay Kamb (University of California). Both glaciers were essentially eliminated in Bentley's view, the Hatherton because of bare ice and an impassable headwall, and the Skelton because of severe crevasse problems in the 15-mile stretch from Clinker Bluff to Neve Nunatak.

A memo from Keith Echelmeyer to Bob Bindschadler, Ian Whillans and the Senior NSF Representative at McMurdo (dated 23 November 1993) described a Twin Otter reconnaissance of the Leverett Glacier made the previous day. It presented a favorable impression of the route potential including the statement, “I don't think that the route would require filling in any major crevasses, nor would one have to cross any large ones.”

During a 13 December 1993 LC-130 flight from South Pole along Leverett Glacier Ian Whillans made observations of the route. In a memo to Bob Bindschadler and Dave Bresnahan (NSF/OPP) he describes, for the section between the head of the Leverett and South Pole, blue ice, long sastrugi, and large crevasses, but generally good conditions. Further, he states that “within the Leverett valley there is a nearly uniform gradient with crevassed places requiring care and short, wide sastrugi indicating small wind speed, raising the concern that snow may be soft due to small initial density.”

In the memo “Report on Field Visit to Leverett Glacier, January 1994,” Gordon Hamilton (Byrd Polar Research Center, Ohio State University) documents observations made on a 10 January 1994 Twin Otter field reconnaissance to investigate snow structure, measure slope angles and reconnoiter crevasses. Four Twin Otter landings were made on various parts of the Leverett Glacier, surface snow structure was evaluated and pits dug for snow stratigraphy (snow density profiles included in the report show densities to be near 400 kg/m^3 from the surface down to nearly a meter). Two 7m (approximately) cores were taken for analysis at McMurdo.

The report states “Leverett Glacier...seems to be a good choice for a tractor route..., and the viability of the route along the transantarctic escarpment must also be investigated but assuming that meets specifications (especially snow conditions) then Leverett Glacier is recommended as the route through the mountains to the plateau.”

Two geographic hurdles are identified in “Search for a Safe Tractor Route from McMurdo Station to the South Pole” by Ian Whillans, Gordon Hamilton and Carolyn Merry in an enclosure to a 4 May 1994 letter to Erick Chiang (NSF/OPP). These areas were identified in the course of their work done to identify a suitable surface tractor route between McMurdo and South Pole and presented at the Antarctic Traverse Workshop held in late May 1994. This document specifies as obstacles a) the area of large crevasses east of Minna Bluff and White Island (now known as the McMurdo Shear Zone), and b) the route through the Transantarctic Mountains. Their work to that date had concentrated on the search for a route through the mountains, and this document briefly traces the process of elimination leading to the Leverett Glacier. It concludes with the statement, “Selection has been narrowed to a single good route. We are now considering refinements.”

In July 1994, Gordon Hamilton reviewed USGS aerial photography of the Skelton and Hatherton Glaciers, taken in November 1993. He concludes that the glaciers photographed are no longer considered possible routes for the South Pole tractor traverse.

The motivation for examining these photographs was to see what can be learned and applied to an aerial photography mission of Leverett Glacier, scheduled for late 1994.

Continued studies of the tractor route across McMurdo Ice Shelf (memo dated 24 September 1994) by Ian Whillans, Carolyn Merry, and Gordon Hamilton utilized Landsat Thematic Mapper images. They describe the analysis of images to find a route across the McMurdo Ice Shelf and across the shear zone between the slowly moving McMurdo Ice Shelf and the fast moving Ross Ice Shelf. Reflecting their growing confidence with the Leverett Glacier as the avenue to the polar plateau (based on satellite image and air photo study), they state the shear zone is likely to be the greatest single obstacle along the route from McMurdo Station to South Pole. They also note beyond the shear zone is a street of nearly featureless ice on the Ross Ice Shelf.

Although there are somewhat conflicting viewpoints in the earliest studies mentioned above regarding the suitability of possible routes to the polar plateau (especially the Skelton Glacier), the results of these studies seemed to conclude that only the Leverett Glacier appeared to come reasonably close to satisfing all of the criteria desired for heavy tractor trains.

McMurdo Shear Zone

Satellite images of the zone between the Ross and McMurdo Ice Shelves clearly show a somewhat wrinkled, or turbulent appearance. Extensive crevassing in this zone is quite apparent between the south end of White Island and Minna Bluff. Here, huge open rifts occur and the Ross Ice Shelf is scrapped past the tip of Minna Bluff. Not obvious but strongly suspected were many hidden crevasses along the northern continuation of this boundary between the two ice shelves. Historical travelers across this shear zone have had mixed success, with some falling into crevasses completely unexpectedly and others blithely passing unhindered.

Whillans and Merry (1996) have done comparative studies of “time-lapse” satellite images in the McMurdo Shear Zone to estimate the direction and rates of ice movement. On the basis of the derived ice shelf motions, they were able to make predictions of the areas where hidden crevassing might occur. The orientations and size of crevasses were also predicted. Subsequently, Arcone et al (1996) have performed Ground Penetrating Radar (GPR) surveys (Delaney et al, 1996) of the Shear Zone to precisely identify the zone and nature of crevassing in this area.

Feasibility

All of the parties involved in data collection and route assessment agree that the Leverett glacier represents the most favorable avenue from the Ross Ice Shelf to the polar plateau. Being located about as far as you can travel from McMurdo before beginning to climb is also very beneficial for the tractors. Further, none of the personnel involved in the field assessment identified outright “show stoppers” leaving all of us encouraged that an oversnow tractor train trail is a viable alternative to flying to South Pole.

Immediately following the field studies of the potential traverse routes, Blaisdell was assigned by NSF Office of Polar Programs to use available data to make a first estimate of the economic feasibility of a McMurdo-South Pole surface delivery route. Together with several colleagues, Blaisdell combined tractor performance data with what is know about the terrain along the candidate routes to determine potential delivered loads, fuel consumption, and travel time (Blaisdell, 1999; Blaisdell et al, 1997). The results of these analyses can be stated quite simply; for a modern tractor train traveling along the Leverett traverse route

- Each tractor-trailer unit can deliver to South Pole about 60,000 lb, or 2 times the payload of a single LC-130
- Each tractor-trailer unit, carrying with it round-trip fuel, will consume nearly the same amount of fuel used by a single LC-130 for the round trip
- Each tractor-trailer unit will require approximately 330 hours of driving time to complete the round trip, while the LC-130 makes the round trip in roughly 6 hours (including South Pole on-ground time)

Based on these results, it certainly appears that the margin of benefit is large enough that, even if Blaisdell's analyses are too optimistic, a tractor can compete head-to-head with an LC-130 in terms of quantity of goods delivered per unit of consumed fuel. Obviously the big difference is in terms of speed of delivery and the, as yet undetermined, difference in cost to operate a tractor-trailer unit for some 335 hours compared to an LC-130 for 6 hours.

Indeed, there is precedence for such optimism. The joint French-Italian initiative to build a station at Dome Concordia is being supplied almost entirely by surface transport from Dumont D'Urville using Caterpillar Challenger tractors with sleds and trailers (Fig. 1). This 1120 km (one-way) traverse has been completed 13 times to date and has met with good success. It stands as a good analog to the proposed McMurdo-South Pole traverse. The most recent reports of the Dome C logistic traverse (Godon and Cucinotta, 1997; Godon, 2000) presents values confirming several estimates used in the Blaisdell studies (e.g., average speed, fuel consumption). Additionally, there are many "lessons learned" that will be directly applicable to the USAP traverse, such as the most beneficial mix of personnel, how to select personnel, trail grooming, and how to divide up critical supplies to minimize risk, to name a few.

Figure 1. Traverse operations for the French-Italian Dome C project.

There is less written about the Russian traverse from Mirny to Vostok (1420 km, one way) but it too can be used as an example confirming that it is reasonable to perform surface transportation as a main supply mechanism between two distant stations in Antarctica (Klokov and Shirshov, 1994). This traverse began operation in 1956 and has been performed for many years as the principal supply means for Vostok. It is our understanding that the majority of the difficulties experienced by the traverse in recent years centers around the use of unsuitable (unreliable) vehicles and the lack of appropriate personnel support (both on and off the continent).

Both the Dome C and Vostok traverses experience over 80% of their elevation gain during the first 25% of the journey (when the tractor loads are at their maximum). Additionally, in the first 25% of these routes, called the coastal zone, deep soft snow, large sastrugi, strong winds with blowing snow, and crevasses are added to the steep slopes to challenge the tractors. Despite this, both programs report average outbound (loaded) speeds of 8.5 to 9.5 km/h and average return (unladen) speeds of 10.5 to 13.5 km/h. The current analyses for the 1600 km McMurdo to South Pole traverse (Leverett route), which gains only 5% of its elevation in the first 65% of the journey, estimates an average speed of 7.2 km/h for the outbound trip and 14 km/h for the return segment. This comparison suggests that the envisioned McMurdo to South Pole traverse is basing its analysis on realistic values.

Description of Traverse Option

In its simplest form, the McMurdo to South Pole traverse scheme involves a family of tractor-trailer units traveling along a marked and semi-maintained corridor on a given schedule with the purpose of delivering needed goods. In this, it is no different that any other surface transport operation. For much of the world the routes and the tractors are highly developed and specialized, but there exist surface transport operations in remote and harsh areas (e.g., Sahara Desert, Northwest Territories) that bear similarities to what is envisioned here.

Prior Results

Based on the prior studies noted above, we assume the following to be the most likely parameters for the McMurdo to South Pole traverse.

- The trail will roughly follow the path shown in Figure 2, using the Leverett Glacier to transition from the Ross Ice Shelf to the polar plateau.
- Caterpillar Challenger tractors, probably model C65, will be the prime mover. (The original analysis was performed for the C65 model. Since that time, up-powered models – the C75, C85 and C95 – have become available. However, the biggest advantage of the greater horsepower models is their greater drawbar pull in low gears, where, for this application, the tractors are traction limited rather than power limited. These bigger tractors also provide a bit greater drawbar pull in higher gears as well, but, without a complete analysis, this does not appear to have a big enough impact on the delivered payload to justify their greater cost to purchase and maintain.)
- Tracked 42-ft trailers, matched to the Challenger tractors and using the same rubber-belted tracks, will be the standard cargo carrier for loads. To reduce unnecessary “tare” weight, the trailers will be skeletal and will allow securing a variety of modular loads or loose loads. Other trailers or sledges may be considered

for specialized purposes (e.g., recovery trailer for malfunctioning equipment that can't be fixed on the trail), but these are likely to be few in number.

- Recognizing that fuel is the single largest commodity delivered to South Pole, and that it represents a concentrated and easily configured payload, it is assumed that traverse equipment will be optimized for fuel delivery. To wit, the tracked trailers will be have ample fuel storage capacity to fully load the trailer. The fuel tank(s) will be segmented, have secondary containment, and will be placed to minimize the height of the trailer's CG and to allow modular or loose loads to be placed on the trailer as well.

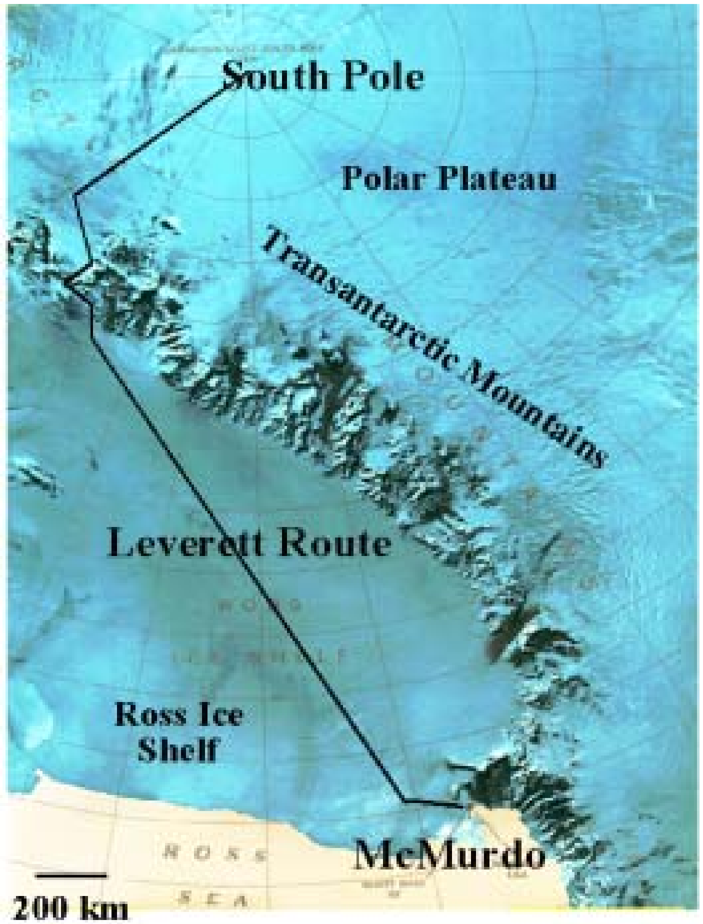

Figure 2. Traverse route using the Leverett Glacier for access from the Ross Ice Shelf to the Polar Plateau.

- Each tractor will be linked to more than one trailer for the traverse. The standard configuration will be one tractor pulling two 42-ft trailers. In some cases a tractor may pull a specialized trailer or sled plus one or more 42-ft tracked trailers.
- A round-trip traverse will require 222 hours of driving to reach the South Pole (66% of total driving time) and 113 hours to return to McMurdo (33%). The tractors consume 15.3 gal/hr, meaning the outbound leg will use 3400 gallons of fuel, with 1727 gallons burned to return. Each tractor will leave McMurdo towing a total payload (gross load minus tare weights) of 95,000 lb. It will arrive at South Pole with 63,800 lb, of which 60,125 lb can be left as delivered payload (the remaining 3675 lb is fuel needed for a portion of the return trip).

New Details

To complete the analysis planned here, further details of the traverse need to be specified. In particular, the envisioned execution of a traverse must be spelled out in order to perform an economic analysis. Several operational schemes can be considered (Table 1); we have discussed these at length, reaching an agreement that what follows is a sustainable and realistic scenario. To be certain, other schemes could be considered and are perhaps practiced by traversing parties, but we believe that the following fits most comfortably into the current USAP operating arrangement. Additionally, it closely matches the pattern used successfully by the Dome C traverse group.

Table 1. Potential daily traverse operating patterns.

	Pros	**Cons**
A. **24-hour operations**	Shortest time on trail Most efficient use of tractors	Need stop time for PM Need 2 or 3 operators per tractor (rotating) Requires sleep (recovery), food prep, eating, etc. while moving Potential psychological impact and physical drain on operators
B. **12 hrs on, 12 hrs off**	Gives adequate time for daily maintenance Gives adequate time for sleeping, eating, socializing while stopped Need only 1 operator per tractor	12-hours driving is long for one operator each day Twice as much time on trail compared to A. Engines at idle for 12 hours or cold starts each morning
C. **Two 8-hr shifts on, 8 hrs off**	Gives brief rest period for sleeping, eating, and socializing (but perhaps too short) Gives adequate time for daily maintenance Requires 30% less time on trail compared to B.	"Off" time is probably too short for complete rest cycle Need two operators per tractor During work day one set of operators will always have 8 hours of "being along for the ride" with nothing to do Engines at idle for 8 hours or cold starts each morning
D. **Two 7-hr shifts on, 10 hrs off**	Gives adequate rest period for sleeping, eating, and socializing Gives adequate time for daily maintenance Requires 15% less time on trail compared to B.	Need two operators per tractor During work day one set of operators will always have 7 hours of "being along for the ride" with nothing to do Engines at idle for 10 hours or cold starts each morning

We have selected a 12-hours on/12-hrs off schedule for operating on the traverse trail (scheme B, Table 1). This strikes us as the most efficient use of the combination of tractors and operators. Schemes A, C, and D (Table 1) all require more than one operator per tractor. (One could argue for having a single operator drive 14-hrs per day, covering both of the shifts indicated in scheme D. However, we think that might exceed the long-term endurance of operators, who will ultimately be expected to perform several round-trip traverses to South Pole each season.) Favoring scheme B, we feel that the extra "cost" of having the tractors not working for 12-hrs per day is more than offset by having a minimum of personnel on each traverse team. Minimizing personnel means increased payload and reduced complexity, since each additional person on-board equates to more food and energy consumption, more waste produced and more personal gear. This scheme also maximizes productive operator hours by not having second (and perhaps third) shift workers riding along with nothing to do during their off-duty hours. And finally, this scheme ensures that there is adequate time for eating, sleeping and maintenance while the train is not moving. By itself, this last attribute may contribute the most to the sustainability of the traverse, by reducing physical stress on operators (proper rest, nutrition, social interaction, and time for communication with the "outside" world) and by ensuring that tractor maintenance is not short-changed for a few extra hours of sleep or a good meal.

We suspect that once a few traverses have run, an "ideal" on-trail schedule will soon become apparent. Also, it is not possible yet to know how many days should be planned for weather delays. In this analysis we will principally work from the basis of required driving hours to make the trip, with a buffer available for a few weather days.

It is traditional, and clearly prudent, for tractors to form convoys when traveling the traverse trail. In polar tradition a group of vehicles making an extended trip is called a "swing." A number of factors can be taken into account when determining the size of a swing. From a safety viewpoint, it should probably not be less than three tractors. The Dome C traverse group have determined that, given the amount of tractor fuel and personnel and tractor sustenance materiel needed (living module, food, generator, medical supplies, spare parts, etc) pay-load is not delivered until 3.6 tractors have been included in a swing. They typically operate eight tractors per swing.

We chose to start with a plan for 5 tractors per swing. We assume that there will be a minimum of 5 and a maximum of 7 staff on each swing. (Personnel skill mix is not addressed here, but some mention of recommended specialties is given later when calculating costs.) Current technology is at a point where it is possible to have as few as one of the swing tractors driven by a person, the remaining tractors being "slaved" electronically to the first. Both military and civil applications have shown the viability of this approach, which would be ideal for the relatively slow-moving traverse. In time, we see the traverse moving toward this means of minimizing staff, once the route and operations are well known. Such a semi-autonomous operation would also make routine use of remote diagnostics tools, which are also available now on the commercial market.

We envision that each tractor will tow two 42-ft trailers, meaning that each swing contains 20 module positions, if we define a position as a 20-ft long by 8-ft wide area of trailer deck. For safety reasons, two separate life support modules will accompany each swing. One should be a primary and complete living module with berthing, food preparation and dining areas. A second, back-up survival module (not necessarily as plush as the primary module) should be included and be physically separated from the primary unit to prevent both being lost in a single mishap (fire, roll-over, etc.). Each module should be capable of berthing and feeding the whole swing team. However, for routine operations, we envision that the primary module will be used to berth up to four and will be the primary kitchen/dining facility. The back-up module will supply additional beds and a lounge area during routine operations. Food stores should be divided and included in both habitat modules. The back-up module should have its own sustenance power production capacity and a snow melter for potable water. Both modules should have a complete set of communications equipment and critical medical supplies. A third module will include spare parts, contain primary energy production and potable water generation facilities, as well as a bathroom (head). It is anticipated that all wastes will be collected in a holding tank and be processed in the McMurdo waste treatment plant at the conclusion of each swing.

One option for these three modules is that they have their own running gear (tracks or skis) and be towed in conjunction with the 42-ft trailers. However, since this adds tare weight and an extra source of motion resistance, we plan that the modules be paced on the standard 42-ft trailers. Assuming that each of these three modules can be fit into a 20-ft module position, this leaves 17 open positions on the standard trailers. While this might seem like a loss of payload capacity for the trailers, recall that the standard 42-ft trailers have below-deck fuel storage capacity equivalent to the maximum trailer payload. Since the sustenance modules are not expected to be very heavy, the trailer should still be able to carry a maximum load.

Prior results give 222 hours driving time from McMurdo to South Pole and 113 hours for the return (Blaisdell et al, 1997). Using travel scheme B (Table 1), this results in the outbound trip occupying 18.5 calendar days, with 9.5 needed to return. Allotting one full day for unloading, backloading (if required) and "socializing" at South Pole, this yields a 29-day round trip. Giving credit to Mother Nature and Murphy, we assume that there may be a few down days, and call this a month's journey. An annual traverse plan based on these assumptions is presented in Table 2. Each team performs three round trips each season, with a 10-day break in McMurdo between each swing. This time in McMurdo is set aside for the operators to "recover," and for them to perform major maintenance on their equipment. Additionally, they will make preparations for their next swing (e.g., putting together loads, checking weather forecasts). This schedule fits exactly with the current USAP summer season for both McMurdo and South Pole. Thus, the personnel contract period is no different than for other seasonal workers. Additionally, air support is available throughout the traverse period.

Table 2. Proposed annual traverse schedule.

	leave MCM	arrive NPX	leave NPX	arrive MCM
TEAM 1				
Swing A	20 Oct	8 Nov	10 Nov	20 Nov
Swing C	30 Nov	19 Dec	21 Dec	31 Dec
Swing E	10 Jan	29 Jan	31 Jan	10 Feb
TEAM 2				
Swing B	25 Oct	13 Nov	15 Nov	25 Nov
Swing D	6 Dec	24 Dec	26 Dec	5 Jan
Swing F	15 Jan	3 Feb	5 Feb	14 Feb

The scenario presented (scheme B, Table 1), with the Table 2 schedule, achieves 30 tractor trips to South Pole each season. Prior results calculate that each tractor delivers just over 60,000 lbs to South Pole on each trip (Blaisdell et al, 1997). However, this did not include the impact of carrying along the support modules. We assume that the three modules will total about 4000 lbs. This means that each of the six swings deposits a payload of 280,000 lbs (5 x 56,000). A season's traverse activity delivers 1.68 million lb, or 243,500 gallons of fuel. Estimated annual South Pole fuel requirements (once the reconstruction effort is completed in 2005) are 3.23 million lb, meaning that this traverse scenario delivers 52% of the station's needs.

We plan that the traverse operation be staged from the Williams Field complex. While the equipment will be serviced in McMurdo, we think it will be wise to keep the traverse-related loading and unloading activities, and parking of equipment (during the summer season) out of the way of "town" operations.

Contingency Considerations

Figure 3. USAP Challenger 65 utility tractor.

It is inevitable that there will be equipment break-downs along the trail. However, we anticipate using modern, proven equipment, thus minimizing break-down risk. For example, the proposed tractor type, the Caterpillar Challenger (Fig. 3), has worked in the McMurdo area for some years, and more recently at South Pole, with good success and providing knowledge of its strengths and weaknesses (e.g., a mean major overhaul interval of 12,000 hours in the USAP, compared to 7,000 hours for the typical agricultural user). The trailers are also a known commodity for the USAP (Fig. 4). Most, if not nearly all of the swing team members will be experienced mechanics, with specialized training on the traverse equipment. It may also be possible that the traverse equipment will be leased from the manufacturer. This could be attractive for the USAP because of the potential for the manufacturer to provide major maintenance and to routinely refresh the fleet of tractors. (An added benefit of leasing is a smoothed capital investment load.)

We expect that, occasionally, a tractor or trailer will go down "hard," meaning that it is not a simple matter for the traverse crew to achieve a fix in the field without additional support or a major delay. For such instances, we envision two potential solutions. In the first, a ski aircraft (or helicopter, if within its range) is dispatched to the site of the break-down with specialized parts, mechanics, and perhaps a temporary shelter to achieve the fix. If this is not practical, it is expected that there will be a "low-boy" trailer for recovering and returning to McMurdo the down equipment. We suggest that, upon such a breakdown, the swing proceed on, leaving the malfunctioning equipment along the trail. The low-boy, towed by a Challenger tractor, would leave with the next departing swing (which would configure itself to pick up the delayed load), carrying on the low-boy a replacement for the damaged equipment. At the break-down site, the recovery vehicle would drop off the replacement and pick up the broken down equipment. Before having departed McMurdo, the travel schedules of the swings will need to be coordinated so that, we hope, the low-boy can return in the company of a swing homebound from the South Pole.

A medical emergency could also be encountered on the traverse. We plan that at least one of the team has a high level of emergency first response training, that at least two have advanced life-saving training, and that all have some level of wilderness first aid proficiency. A medical evacuation by air will be the recourse for any treatment required that is beyond the capacity of the swing team to tackle. Of course, all traverse members will have previously been screened physically and psychologically to a level similar to USAP winter-over candidates.

Figure 4. Tandem tracked trailers on traverse from Marble Point to McMurdo.

The schedule shown in Table 2 leaves little margin for weather or mechanical delays. We anticipate that the ten days between swings for each traverse team will be more than adequate for the tasks that must be accomplished in McMurdo, and expect this to be the buffer for unexpected occurrences.

Timeline for Development

We anticipate that the development of the traverse operation will pick up from where it left off at the end of the 1995-96 season (Evans, 1996). We expect that there will be a small research phase, followed by a pioneer phase leading to a ramp-up to the desired full operational status. Procurements will need to be made along the way and constitute a major item of the development process because of the long time period between the decision to purchase and the actual delivery of the equipment at McMurdo (under ideal conditions this is about 18 months for customized heavy equipment). Table 6 shows three potential development periods. To stand a chance of achieving the aggressive schedule (which doesn't establish a "production" traverse until the 2002-2003 season), the USAP would have to take action immediately. Given the cost and commitment associated with the traverse, and the fact that the USAP has not yet decided that the traverse is its most desirable option for increasing available LC-130 hours, this schedule is probably not realistic. The conservative and moderate timeframes shown could reasonably be achieved with a USAP "go" decision during FY00. However, neither of these schedules establish routine operations until at least the 2003-2004 season.

Impact of Traverse Operation on Current USAP

As presented here, the traverse is principally a self-contained addition to the current USAP. Thus, we feel that its influence on current operations is minimal, in terms of perturbations or disturbances to the USAP standard operating procedures. Areas of significant impact and interaction with the current system are shown in Table 7. A timeline is given in Figure 5 showing how the traverse fits into the current USAP summer season.

Table 7. Items of major impact by the traverse on current USAP operations.

Location	**Impacts**
CONUS	Traverse will likely require an EIA/EIS The volume of equipment needed will require considerable specifier/purchaser time during brief period Load planners will need to learn during first few years how best to divide and schedule tractor and LC-130 loads Weight and cube of traverse equipment in vessel
CHC	No significant impact
MCM	Heavy Shop space and traverse equipment parts warehousing Addition of swing operators to population count Dedicated dorm space for swing operators, who will be in town only about 50 days over course of summer season Coordinator and coordinator's assistant staffing and office space Weather support Trail food ordering, stocking, and preparation Earlier deployment of fuel hose to Williams Field Reduced overall fuel usage from MCM tank farm Trail waste added to MCM waste stream Traverse does not assist in current-season delivery of vessel cargo
NPX	First tractor train arrives about one week following traditional flight opening Relief of "fuelie" teams Transient lodging, shower, meal for swing operators at routine intervals Reduced frequency/volume of flight missions Traverse does not assist in current-season delivery of vessel cargo

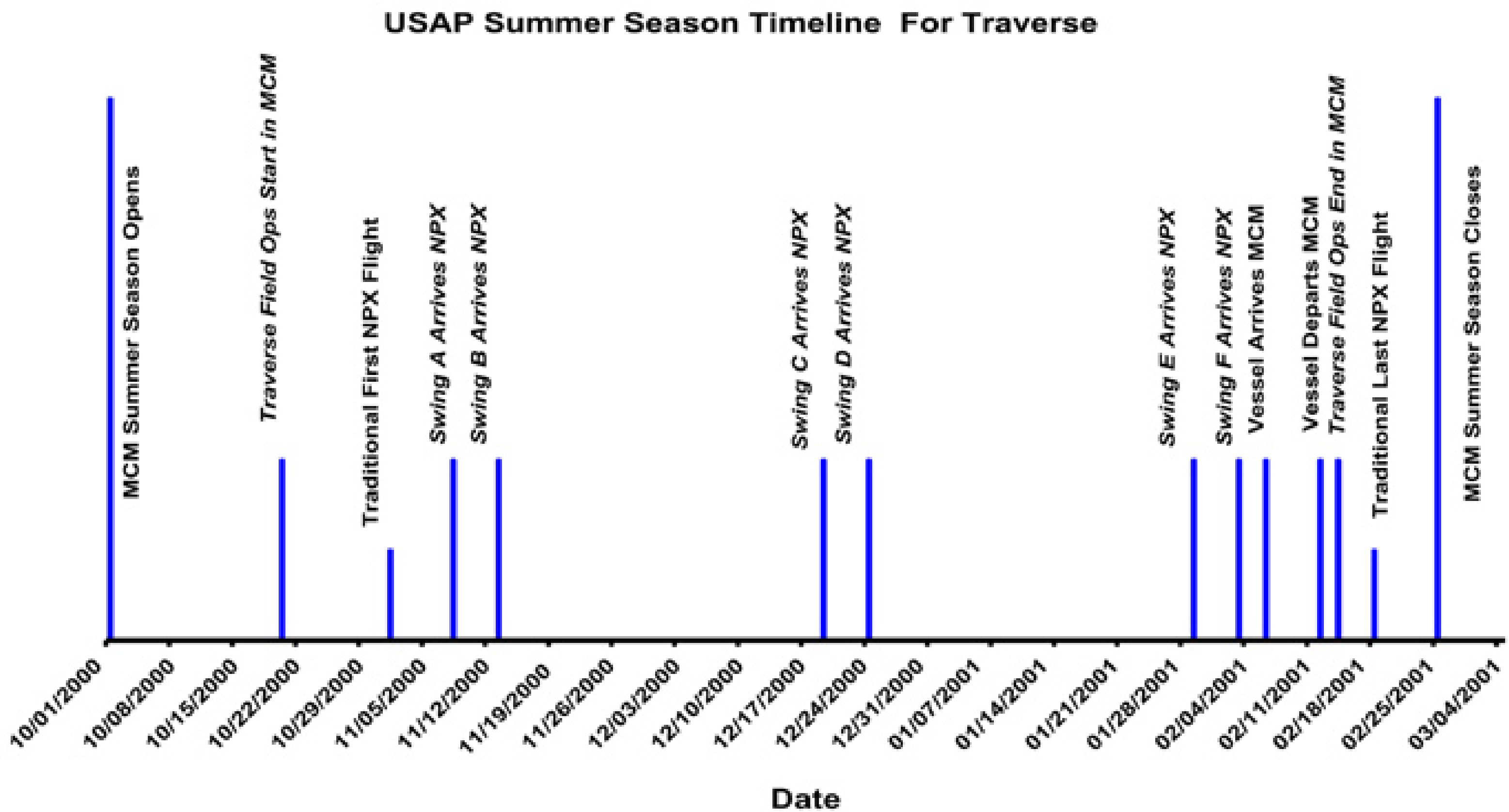

Figure 5. Traditional USAP summer season showing timing of traverse operations as given in Table 2.

Evaluation of Risk

We have identified nine real or potentially significant risks (Table 8). For each, we made an estimate of the likelihood of it occurring, the impact to the USAP if it should occur, the cost (not in dollars, but in increased pressure on the current USAP system), and the factors that can assist in mitigating or eliminating the occurrence of such a risk factor. It is encouraging that the USAP has considerable prior experience with the most likely to occur of these risk factors. Also, it is fortunate that the possibility exists to exhibit a reasonable amount of control over most of the new and unique risks.

Overall, the risks shown do not appear to represent a major cost concern to the USAP, nor do they put equipment and personnel at any more significant peril than is routine in the current program.

Direct and Indirect Benefits Associated with the Traverse

There are a number of attractive features of the traverse as a means of reducing LC-130 airlift to South Pole. Prior analyses (Fig. 6) show that the only advantage of the LC-130 aircraft over a tractor train for deliveries to South Pole is the very short time en-route. For the other factors, the tractor is able to deliver slightly more than twice the payload with the same amount of consumed fuel. Since fuel is the major commodity delivered to South Pole, the need for it to arrive from McMurdo in 3 hours, versus in 20 days, is not important (as long as it does arrive!).

The relationship between LC-130 and tractor train (5-tractor swings) deliveries to South Pole is shown in Figure 7. We assumed an LC-130 payload of 26,000 lbs, since this represents the recent average delivered payload. This means that the tractor train to LC-130 ratio is close to 1 swing to 10 flights (the actual ratio is 1:10.77). We show in Figure 7 the recommended initial production traverse operation of six swings per season, thus relieving the need for about 64 LC-130 flights. This represents delivery of close to 1.7 million pounds of goods, slightly over half the required annual fuel delivery to South Pole. This scenario yields to the USAP more than 380 flight hours that could be reprogrammed for science or other missions.

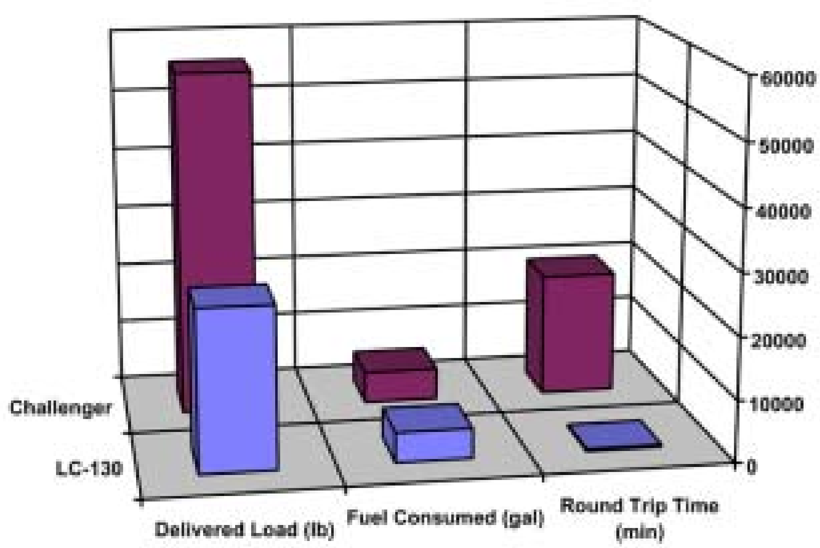

Figure 6. Comparison of delivery statistics for LC-130 and single tractor.

The current (FY99) number of completed South Pole flight missions is 264. A significant fraction of these flights are associated with the Station Modernization effort, which will be completed in 2005. A realistic "steady state" flight season is 180 missions. It is impractical to plan for traversing to completely compensate for LC-130 missions,

Table 8. Analysis of risk.

Risk Factor	Estimated Probability of Occurrence	Estimated Impact	"Cost"	Mitigation Factors
Severe Weather	Very likely	Minimal delays over course of season	Eats into 10-day interval between team's swings	Well established route; good forecasting; Reliable navigation systems
Equipment Breakdown	Likely	Minimal delays over the course of a season; occasional "tow truck" mission	Delay of 1 or more trailer arrival at NPX; Cost of "tow truck" mission and repair, or cost of on-site fix	Rigorous and aggressive PM in McMurdo and on trail; Use of proven equipment; Appropriately trained swing staff (mechanical and psychological)
Trail Deterioration (sastrugi, soft snow, opening of known crevasses)	Probable	Slows speeds; Increased operator discomfort; Increased trail maintenance efforts	Eats into 10-day interval between team's swings; Potential for need for extra personnel for trail maintenance	Understand trail and identify all en-route crevasses; Understand most effective trail maintenance techniques (including crevasse mitigation)
Undetected crevasses	Very low	Potentially devastating	Major delay for determining detour or mitigation effort; In bad case, loss of equipment, payload and need for major recovery effort; In worst case, personnel injury	Complete understanding of glaciology of route; Complete GPR survey prior to operations and frequently thereafter (at least for first several years)
Fuel Spill	Extremely low	Loss of payload; PR nightmare	$1.24 per gallon; Cost of clean-up; Delay for tank repair	Secondary containment on tanks; Regular prescribed daily tank inspections; Trained quick-response clean-up team on call

Table 8. Analysis of risk (continued).

Risk Factor	Estimated Probability of Occurrence	Estimated Impact	"Cost"	Mitigation Factors
Personnel in Remote Field	Certain	Extra 10-14 (or more) persons in deep field	Potential for needed rescue/relief mission	Is an extension of current deep field parties; Have experience with ITASE moving deep field party; After first couple years this becomes a familiar operation
Psychological "Load" on Swing Team	Moderate to low	Unexpected staff turn-over; Morale problems for swing team	Delays due to less-than-efficient operation; Cost of mid season reassignments or hiring actions	Careful selection and proper screening of swing personnel; Proper allowance for R&R between swings; Proper allowance for rest, nutrition, social contact while on trail
Medical Emergency	Low	Delay of swing; Loss time	Eats into 10-day interval between team's swings; Medivac or rescue mission	Careful selection and proper screening of swing personnel; Routine check-ups after each swing; Proper allowance for R&R between swings; Proper allowance for rest, nutrition, social contact while on trail
NGA Use of Trail	Low	Occasional delay of swing; Trail damage; NGA need for assistance; More NPX visitors	Eats into 10-day interval between team's swings; Increased trail maintenance; Humanitarian rescue	Don't advertise trail OR Vigorous advertisement of no-assistance policy
Development Doesn't Progress or Yield as Planned	Low	Economics do not develop as favorably as they were assumed; Future plans based on traverse need to be modified	Traverse deliveries cost as much or more than air delivery; Traverse operation adversely impacts normal USAP summer operations; Underutilized equipment	Monitor development during pioneering phase; Continue to compare estimates/results with international examples (e.g., Dome C traverse)

since personnel and critical cargo (e.g., science equipment, mail, food) will always need speedy delivery. Additionally, there is a practical limit to the number of swings (i.e., swing operators and equipment) that could be performed in a season. It has been suggested (E. Chiang, personal communication) that at least 60 annual flights is a minimum desirable over the course of the South Pole 100-day summer season.

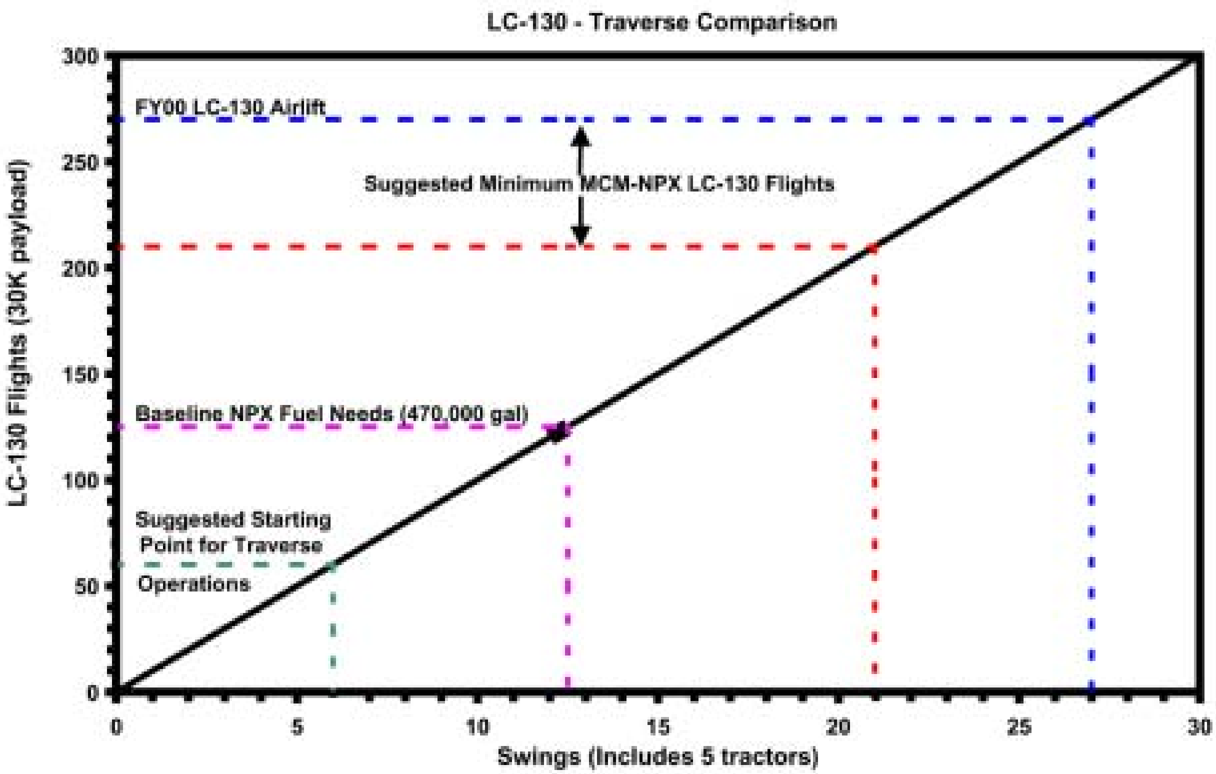

Figure 7. Potential for Traverse Contribution to Reduced LC-130 Airlift.

Given a baseline of 180 LC-130 payloads to be delivered to South Pole, with 60 flight missions desired, leaves 120 full aircraft payloads or 12 tractor train swings required to make up the difference. This is twice the scenario presented here and is probably doable. However, the most cost effective way to increase the number of swings to South Pole is to increase the number of trips each tractor makes each season (vice the costly purchase of more tractors and trailers and their associated maintenance tails). We think that, given the length of the delivery season and the length of the tractor train journey, it is probably not feasible to squeeze more than four swings per season out of a given tractor. This would require, in our estimation, swing operators to “tag” at the end of each swing, so that the tractor sits idle only for the length of time necessary for its Heavy Shop check-up. An alternating set of swing teams would work the traverse operation, and perform other duties in McMurdo in between stints on the trail. (The total number of swing operators in this scheme is greater than our original arrangement, but they would be multi-tasked personnel, so the extra cost may be minimal.) Working with the two 5-tractor groups we have specified in this exercise, this enhanced scenario would produce eight swings per season. Eight swings equates to 40 tractor loads, or 86 full-payload flight missions, representing 2.24 million pounds delivered. Under this scheme, 86 missions, or 515 hours of LC-130 flight time is given back to the USAP for alternate use.

An advantage of the traverse option is its ability to provide a flexible and distributed relief of LC-130 hours. Provided the traverse principally delivers fuel the 380 (or 515) hours that the traverse frees can be used at any time in the season. (For the first few seasons, we suggest that very few time-critical items travel by tractor train.)

The traverse further provides greater flexibility to the USAP in that payloads are not constrained to the 9-ft x 9-ft cross-section imposed by the LC-130 cargo bay. Long loads may also be carried with greater ease with the traverse system.

We anticipate that the swing operators will be trained in loading and unloading their cargo, as well as driving. Thus, the cargo and fuel teams at South Pole would be relieved of the need to unload 1.8 million pounds (under the 6 swings per season schedule) or 2.4 million pounds (with 8 swings per season). We don't know what fraction of their seasonal hours this represents, but it is labor hours that can be put to other use by the small logistic staff at South Pole.

A less direct advantage of the traverse is the development of a new corridor of access. The recent ITASE project has resurrected science traverses in the USAP; the number of projects involved in this traverse indicates there is considerable interest in the type of research that can be done by a moving, ground-based field party. The traverse trail, and its "frequent" traffic will offer scientist the potential to perform projects along the direct transects of the Ross Ice Shelf, the Leverett Glacier through the Transantarctic Mountains, and a portion of the polar plateau. Additionally, spurs could be developed off the traverse trail to suit specific science needs, with drop-off and pick-up or re-supply at the trail-head by passing swings. During the 1995-1996 traverse route feasibility study, and since then, a number of scientists have approached one of us asking about when the traverse would be operational, with the intent of using it as a portion of the USAP infrastructure capable of supporting their research interests.

Lastly, the traverse has some benefit in its ability to act as the development platform for future and more complex science traverses. The lessons learned and the equipment developed for the South Pole logistics traverse will have direct application to any such USAP activities.

Analysis and Conclusions

The evidence gathered to date, from the field and from "paper analyses" such as this, suggest that the traverse is truly technically and economically feasible. We would feel like classic optimists in making such a statement were it not for the availability of figures for the Dome C traverse, which bears a number of similarities to the proposed McMurdo to South Pole traverse. In every case, we have estimated values, rates, durations, etc based on experience, intuition, and available USAP data, only to find that the number arrived at is very close to what the Dome C operation have reported for their operation.

In economic terms, our analysis is completed as shown in Table 9. We have chosen a 10-year linear amortization period for the capital cost of equipment and for completing the development of the traverse trail and Standard Operating Procedure (SOP). This is based on the expected minimum life of the tractors.

The “bottom line” is represented in Table 9 in relation to two different frames of reference, cost per “saved” LC-130 South Pole mission and cost per pound of payload delivered. We don’t know how the values of $21,930 and $16,320 per saved LC-130 mission (for the 6- and 8-swing options) compare to the actual cost of the USAP contracted LC-130 service. However, this appears to be close to the costs we have heard referenced, and is certainly less than the approximately $5000 per hour charged for the purchase of Military Airlift Command (MAC) Special Aircraft Airlift Mission (SAAM) C-130 time.

Table 9. Economic analysis of Traverse Option

		VALUE ($)
Up-Front Costs		
	Development	510,000
	Capital Investment *	7,455,000
Operational Costs		
	Annual Cost *	667,000
	10-Year Cost *	6,670,000
10-yr Linear Amortization of Up-Front Costs		
	Development	51,000
	Capital Investment	745,500
Total Cost		
	Annually	1,463,500
	Over 10 Years Operation	14,635,000
Comparative Value		
In Cost per LC-130 Mission Relieved		
	6-Swings/Season Scheme (64 missions releived)	21,930
	8-Swings/Season Scheme (86 missions relieved)	16,320
In Cost per Pound Delivered		
	6-Swings/Season Scheme (1.68 M lb delivered)	0.84
	8-Swings/Season Scheme (2.24 M lb delivered)	0.63

*Leasing tractors would reduce capital investment and increase annual operating costs. Lease cost is not known at this time, so comparison is not possible.

In terms of delivery costs, the traverse options show a rate of $0.84 and $0.63 per pound. (The Dome C traverse operation reports an overall transport cost of $1.36 per pound, includes all development cost for their traverse). Again, we don't know what is the cost for LC-130 delivery.

We conclude from this and prior analyses, that the traverse has significant technical and economic merit, especially when viewed as a means to relieve a portion of the LC-130 airlift missions currently providing logistics support to South Pole. There may even be an environmental argument for the traverse, given that aircraft consume more fuel (4800 gal) than they deliver (3800 gal) with each dedicated South Pole fuel mission. (Each tractor consumes 5100 gal while delivering 8100 gal.)

Certainly, there will need to be refinements to the numbers and scenarios presented here and in prior studies. However, there seems to be convergence and good agreement among the various studies, suggesting that, even when viewed from different perspectives, these calculations are reasonable. Even better, the well-documented Dome C traverse experience is proving that not only are these estimates supportable, but that a sustained logistics traverse can be operated with acceptable and manageable levels of risk.

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